Erbium-Doped Waveguide Amplifier (EDWA)
Technology and Components
Jacob L. Philipsen (1), Carsten L. Thomsen (1), Lasse Leick (1), Yueqiang Shen (1), Peter C. Nielsen (1),
Christian Laurent-Lund (1), Morten G. Dyndgaard (2), Thomas Feuchter (1)
(1): NKT Integration A/S, Blokken 84, DK- 3460 Birkerød, Denmark, E-mail: jph@nktintegration.com
(2): COM, Technical University of Denmark (DTU), Building 345V, DK- 2800 Kgs. Lyngby, Denmark

Abstract: EDWA technology is now commercially available and forms a compact and cost-effective alternative to
the EDFA as a key building block for amplifying and controlling signal power in multifunctional subsystems-on-a-
chip. We review the current status of EDWA technology and its applications.

Introduction
Optical amplification with Er-doped glass as the gain
medium has been a key enabler for Dense
Wavelength Division Multiplexed (DWDM) optical
transport systems. Leveraging on the fundamental
properties of Er in a glass host, the Erbium Doped
Fiber Amplifier (EDFA) has demonstrated high gain,
low noise, and full compatibility with DWDM signals.
Presently important trends in optical telecom are the
evolution from point-to-point transport systems
towards optical networks and the evolution from
discrete optical components towards integrated
optical solutions based on Planar Lightwave Circuits
(PLC). The latter evolution is a prerequisite for the
former, since the increased complexity of an optical
network can only be handled in a cost-effective
manner by the introduction of integrated optics and its
wafer-manufacture economies of scale. In these
multifunctional PLCs, amplification and dynamic
power level control will be important enabling
functions.

Erbium-Doped Waveguide Amplifiers (EDWAs) offer
these functionalities at a low price-per-function, and
this has over the past few years driven EDWA-based
devices from research labs to commercialization [1, 2,
3]. This article reviews the present status of EDWAs,
with focus on silica-on-silicon devices and their
applications.

Process
In a waveguide amplifier, the background losses as
well as the physical dimensions limit the amplifier
dimensions. Making EDWAs therefore require careful
host selection to ensure a high solubility of Er, and EDWAs in glass hosts ranging from P-doped silica [8] and Phosphates [5, 6], over Al-doped silica [7] to pure Alumina [8] have been investigated successfully.
Phosphate glasses enable high Er concentration with
a low degree of clustering and are attractive hosts for
EDWAs made by ion-exchange. Net gain of more
than 2 dB/cm has been demonstrated in such glasses
[5], but with a narrow gain spectrum compared to
EDFAs, hence limiting the effective bandwidth.
Al-doped silica and Alumina enable high Er
concentration with a low degree of clustering and
provide a broad gain spectrum similar to that of
Er/Al/La-doped fibers. The refractive index of Al-
doped silica can be controlled by further doping with
Germanium to allow low loss coupling to silica fibers
and standard waveguides. We have therefore chosen
Al/Ge-doped silica as the host material for
manufacturing EDWAs.

Our EDWAs are formed in a three layer structure. The
substrate is a 6 inch Silicon wafer with a layer of
thermally grown silica. The Er-doped core layer may
be deposited by Plasma Enhanced Chemical Vapor
Deposition (PECVD) [9], flame hydrolysis [4] and
sputtering [7, 8]. We have chosen the PECVD
process to yield excellent uniformity of thickness and
refractive index. Furthermore, the process is a
rapid, low temperature process with very low surface
migration of the Er ions, which minimizes the
formation of Er-clusters during deposition. Er- and Al-
containing precursors are added to the gas mixture
during the deposition, thereby forming a Ge/Al/Er-
doped silica layer with accurate control of the
composition. The core layer is patterned to
waveguides using photo-lithography and Reactive Ion
Etching (RIE) and finally, PECVD is applied for
depositing the boron and phosphorus co-doped
cladding layer. The combination of advanced PECVD
and RIE processes enable realization of waveguides
with extremely low propagation losses as we report
elsewhere [2].

For multifunctional components it is required to
integrate waveguides with and without Er doping, as
unpumped Er-doped waveguides have absorption at
signal wavelengths. A composite core layer can be
formed by a repeated series of deposition, patterning and
etching processes using two complementary masks. Subsequently the composite core layer is
patterned with one mask, whence the horizontal
alignment between the Er-doped and undoped areas
is inherently perfect. The vertical alignment depends
on the precision of the etch depth and layer thickness.
The achieved reproducibility of 0.1 µm gives an
interface loss of 0.022 dB/interface (see Fig. 1B) and
a back-reflection below -70 dB [10].
Performance
To achieve sufficient length, our planar amplifier is curled up in a spiral. By optimizing both fabrication and design we have achieved an ultra-low propagation loss of 0.015 dB/cm [2]. This enables high gain as it allows for longer amplifiers with lower Er-concentration, thus increasing the efficiency of the Er-ions [11].

Fig. 2 shows the measured gain and noise figure spectra with -30 dBm input power and 100 mW of 980 nm pump power.

The graph contains data for an EDWA optimized for high gain (closed symbols) and a 40% shorter test EDWA (open symbols). The optimized EDWA has a peak gain of 31.5 dB (1532 nm), a C-band (1528-1562 nm) gain of 23 dB and a C-band noise figure of 5.3 dB. In comparison the test EDWA has 18 dB C-band gain and a noise figure of 4.6 dB. The slight increase of noise figure at high gain is caused by the backwards traveling ASE reducing the population inversion at the amplifier input.

To measure the gain spectrum at higher input powers, a 1550 nm laser is used to saturate the EDWA. The saturation laser is multiplexed with a weak input probe signal prior to the EDWA and the signal gain is inferred from a measurement of the EDWAs output spectrum. Fig. 3 shows the measured gain and noise figure spectra with -10 dBm input power and 100 mW of 980 nm pump power. Fig. 3 contains data for the same EDWAs as fig. 2. The EDWA, which was optimized to small input signal, has a C-band gain of 17.4 dB and a noise figure of 4.7 dB, whereas the shorter test EDWA has a C-band gain of 15.8 dB and a noise figure of 4.0 dB. A comparison with fig. 2 shows that the difference in gain between the EDWAs has decreased with the signal power. The reason is that the optimum EDWA design depends on the signal levels and that an increase in signal power moves the optimum towards shorter length. Furthermore the noise figure has decreased with the signal power due to reduced backward ASE.

At further saturation, an input power of 0 dBm leads to an output power of 7-7.5 dBm for the above described EDWAs, whereas an EDWA optimized with respect to output power gives 10 dBm, corresponding to a conversion efficiency of 10%.

Comparison between different EDWA technologies is difficult as the field is dominated by commercial vendors, whence results are not published. However, to the best of our knowledge the 23 dB C-band gain with 100 mW of pump power is the highest single-pass small signal EDWA gain ever reported.
Modeling
In contrast to Er-doped fibers, the EDWA length is defined during the fabrication, which limits the possible post fabrication adjustment to changing the pump power. Hence a reliable numerical model is required for optimization of EDWAs before fabrication. As no accurate commercial software exists we have developed our own numerical model. The model takes ion-ion interactions into account [11]. Experimental values were used for the upconversion constant, the propagation loss, the fiber to chip coupling loss, the Er cross-sections and the Er concentration. The pump and signal field distributions were calculated with an effective index method and it was verified that the measured and calculated optical mode profiles are similar. The model includes forward and backward amplified spontaneous emission (ASE) in the signal band. The coupled differential equations for the pump, signal, and ASE intensities are solved by iterative numerical integration along the length of the waveguide amplifier using a Fourth order Runge Kutta method. The gain and noise figure are found as described in Ref. 12 [12]. A detailed description of the model can be found in Ref. 13 [13].

To validate the model we have compared the measured and simulated EDWA performance. Fig. 4 shows the measured and simulated peak gain as functions of the pump power for three different input signal levels. The agreement between the measured and simulated values is excellent. For small pump powers the gain increases rapidly with pump power and optical transparency is reached at 20-30 mW. At larger pump powers of ~100 mW, the gain curve flattens out, and at a pump power of 400 mW, a maximum gain of 40 dB is obtained, both for calculated and measured results.

Fig. 4: Measured (symbols) and simulated (lines) peak gain as functions of the pump power for input signals of -30 dBm (triangles), -10 dBm (circles) and 0 dBm (squares). The EDWA design is optimized for small signal gain with 100 mW of pump power.

The figure demonstrates that our model is accurate and can be used under a large number of different conditions. Hence it provides us with a valuable tool for designing EDWAs to meet any required specification.

Applications
The simplest application of EDWA technology is a single amplifier including passive functions such as input and output tap couplers, pump/signal multiplexer, and pump kill filter on a single chip. Both single channel and DWDM amplifiers for metro and pre-amplifier applications have been demonstrated [1, 3]. However, pushed by the price pressure from low-cost EDFAs, this mainly has niche applications, such as integrated pre-amplifiers in receivers, in which the reduced form factor is a decisive competitive factor.

Next step will be the integration of EDWAs with other passive functionality. Figs. 5 and 6 show the combination of a DWDM EDWA preamplifier with a 40-channel AWG demultiplexer. The EDWA and AWG devices were realized on separate chips, but with fully compatible (Er-doped respectively undoped) manufacturing processes, allowing for monolithic integration as described in section 2 of this article. Over the C-band, the inferred combined gain for the EDWA/DEMUX varies from 15.6 dB (1540 nm) to 22.1 dB (1532 nm), measured at channel peaks. The EDWA/DEMUX represents a very cost-effective way of enhancing DWDM receiver sensitivity, since the monolithic addition of an EDWA to the AWG DEMUX implies virtually no extra pigtailing and packaging cost (apart from the cost of a discrete pump laser and an isolator). For this type of integration, PECVD-processed silica-on-silicon PLCs have the advantage of allowing the very high process uniformity required to make state-of-the-art AWGs.
As integrated optics evolves from single-functionality chips (splitter, Arrayed Waveguide Grating (AWG) etc.) towards multifunctional subsystems-on-a-chip (Variable Multiplexer (VMUX), Reconfigurable Optical Add-Drop Multiplexer (ROADM) etc.), the EDWA will become a key building block for amplifying and controlling signal power levels. Control may be obtained by adjusting the pump power to the EDWA to achieve the desired output signal power. Compared to the classical scheme of adjusting signal powers by Variable Optical Attenuators (VOA), the “Variable Optical Amplifier” has the advantage of an improved power budget and improved system signal-to-noise ratio, because channel powers are equalized by being raised to a common high level instead of being decreased to a common low level.

An example of such an application is the monolithically integrated 4- or 8-port EDWA array demonstrated by several commercial companies. The purpose of this device is to provide individual amplifier control in applications with a single-channel or a band of channels passing through each amplifier. Applications include preamplifier arrays and dynamic gain equalization at wavelength switching nodes such as ROADMs. The desire to standardize such a compact amplifier array module has led to the formulation of a Multi Source Agreement (MSA) for EDWA Arrays [14].

An interesting combination of individual channel gain control and multiplexing is the integration of colorless AWGs (typically 4-8 channels) with equivalent port count EDWA arrays for individual channel power control and a high combined output power. With 10 dBm output power from each amplifier and approximately 3 dB MUX and output pigtail loss, an aggregate output line power of 16 dBm will be obtainable for an 8-channel colorless EDWA/MUX. This is comparable to in-line EDFAs, but with the full channel control of a Dynamic Gain Equalizer (DGE).

**Conclusion**

We have presented a status on EDWA technology, with focus on PECVD-manufactured amplifiers, and have reported a small-signal gain of more than 23 dB over the C-band, obtained with 100 mW of pump power in an extremely low loss Er-doped Al/Ge silicate waveguide. We have also reported a state-of-the-art AWG, which is processed with the same wafer process excluding Er-doping. In summary, EDWA technology has reached a level of performance and maturity that will allow a larger focus on developing applications, such as loss-less/amplifying Planar Lightwave Circuits with advanced functionality.

**References**

2. Leick et al, Submitted to ECOC 2003